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On the visibility of luminance fluctuations in television pictures, and exposure variations in motion picture film

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Summary

The use of discharge lamps as light sources in motion picture film work can lead to a cyclic variation in frame-to-frame exposure. This in turn can cause the overall luminance of the displayed picture to fluctuate. This Report describes an investigation of the visibility of such luminance fluctuations over the frequency range 0·1 – 12·5 Hz, and also recommends limits of film exposure variation, over the same variation-frequency range, below which these picture luminance fluctuations should not be visible.

Issued under the authority of

P. Rainger

Head of Research Department

Research Department, Engineering Division,
BRITISH BROADCASTING CORPORATION

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1. Introduction

There is at the present time a growing interest in the use of metal-halide discharge lamps[1] as the light sources in motion-picture film production. The spectrum of the light emitted from a high-pressure mercury lamp containing the iodides of certain 'rare-earth' elements consists of a large number of spectral lines which effectively provide a continuum of radiation suitable for the exposure of colour film stock. The advantage of greater luminous efficacy (i.e. greater light output for a given power input) which such lamps possess, compared to conventional incandescent lamps, can therefore be used in colour film production, particularly in cases where the provision of electrical power is at a premium (e.g. where mobile generators have to be used). Unfortunately, the near-extinction of the discharge at each half-cycle of the (nominally 50 Hz) supply waveform[2] causes the light output of these lamps to have a very pronounced ripple component. The frequency of this ripple is nominally 100 Hz but may differ significantly from this value, particularly if mobile generators are in use. On the other hand, the frame speed of motion picture cameras is accurately maintained at 25 Hz when making film for television, except when slow-motion or accelerated-motion special effects are required. If the supply waveform remains in synchronism with the camera operating cycle, identical samples of the illumination ripple waveform, as defined by the instants of time at which the camera shutter opens and closes, are used to expose successive frames of film. In this case no frame-to-frame variation in film exposure will occur. On the other hand, if this exact synchronism is not maintained, successive frames of film will be exposed by different samples of the illumination ripple waveform. It is then possible that the total light energy will differ from sample to sample in a cyclic manner, the period of this cycle being determined by the rate of change of the time relation between the supply waveform and the camera operating cycle. In this case, the exposure of successive film frames will also vary in a cyclic manner, with the result that a cyclic fluctuation of luminance will be superimposed on the recorded picture. The derivation of the relationship between the frequency of fluctuation of picture luminance and the supply and camera frame frequencies is beyond the scope of this present Report, but it is apparent that in a situation such as exists in all television systems having a field rate of 50 Hz, in which film is scanned at 25 frames per second, the highest fluctuation frequency will be 12·5 Hz (i.e. when alternate film frames give high and low luminance pictures). Lower fluctuation frequencies will occur when the exposure cycle occupies three, four, five or successively greater numbers of film frames.

When carrying out film production work using metal-halide discharge lamps powered from a nominal 50 Hz supply, there is no readily-available method of ensuring that luminance fluctuations will not be present on the recorded material, other than making certain that synchronism between the supply waveform and the camera operating cycle is maintained. Because of practical difficulties in controlling the output frequency of mobile alternators to a high degree of precision, an estimate is required of the frequency range within which the alternator frequency must be maintained, while still ensuring that the resulting luminance fluctuations on the recorded material are not visible. It is possible, given the characteristics of the ripple waveform of the light emitted by a lamp, the shutter angle of the frequencies of the supply and the camera operating cycle, to calculate the frequency and magnitude of the resulting luminance fluctuations. A relationship between these quantities, satisfying the criterion that the luminance fluctuation shall not be visible without at the same time imposing an unnecessarily severe limitation on the magnitude of the fluctuation, would then enable the permissible variation in supply frequency to be determined. The derivation of such a relationship is the subject-matter of this present Report.

2. Experimental and analytical details

2.1. Principle of experimental method

Consider a diffusely-reflecting screen (Fig. 1) illuminated by two projectors. Light from one projector passes through a modulator which is arranged so that the illumination of the screen from this source varies periodically between zero and a maximum value in a 'raised sinusoidal' manner. Light from the other projector passes directly to the screen and the illumination from this second source is of constant intensity. The luminance of a certain area of the screen, at a particular point of observation, will therefore vary (Fig. 2) between the values L_{max} and L_{min}, given by

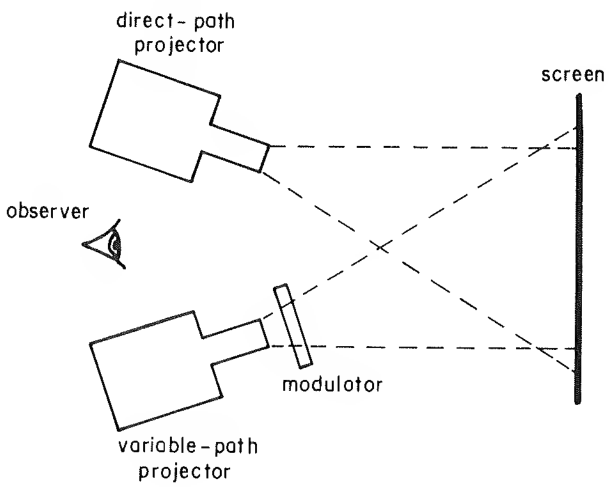


Fig. 1 - Principle of generating a field of view with variable luminance

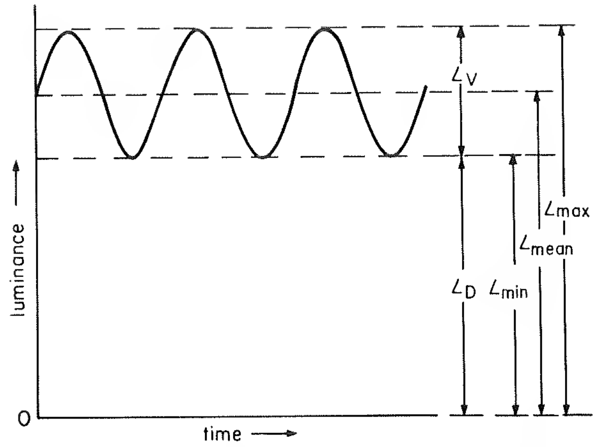


Fig. 2 - Luminance values in variable-luminance field of view

$$L_{max} = L_D + L_V \quad (1)$$

and $$L_{min} = L_D \quad (2)$$

where L_D is the screen luminance due to the direct-path projector on its own.

and L_V is the maximum screen luminance due to the variable-path projector on its own.

Since the variation of luminance with time is sinusoidal, and therefore symmetrical about a mean value, the mean value (L_{mean}) is given by

$$L_{mean} = \frac{L_{max} + L_{min}}{2} \quad (3)$$

$$= L_D + \frac{L_V}{2}$$

In order to distinguish between the magnitude of the fluctuations of screen luminance and the increase in luminance due to the addition of the variable component, it is convenient to express the luminance fluctuations in terms of this mean value. Thus the 'normalised luminance difference' (D_L) is given by

$$D_L = \frac{L_{max} - L_{min}}{L_{mean}} \quad (4)$$

$$= \frac{2L_V}{2L_D + L_V}$$

and the 'luminance fluctuation ratio' (R_L dB) by

$$R_L = 20 \log_{10} \frac{1}{D_L} \quad (5)$$

The results obtained in this Report are expressed in terms of luminance fluctuation ratio value. In some work the luminance fluctuation magnitudes are expressed in terms of the ratio (M_L) of the maximum and minimum luminance values: thus

$$M_L = \frac{L_{max}}{L_{min}} \quad (6)$$

In practice the value of this ratio is such that

$$1 \leqslant M_L < 2$$

and the ratio can therefore be expressed as

$$M_L = 1 + g_L$$

where g_L is the fractional part of the ratio value.

It can therefore be seen that

$$L_{max} = (1 + g_L)L_{min}$$

and $$L_{mean} = (1 + g_L/2)L_{min}$$

hence, from Equations (4) and (5)

$$R_L = 20 \log_{10} \frac{2 + g_L}{2g_L} \quad (7)$$

If $g_L \ll 1$, then

$$R_L \doteqdot 20 \log_{10} \frac{1}{g_L} \quad (7a)$$

In practice, the error involved in using Equation (7a), rather than Equation (7), is less than half a decibel for g_L-values less than 0·1 (20 dB) and less than one decibel for g_L-values less than 0·24 (12·4 dB). The sense of the error is in the direction giving an over-estimate of the luminance fluctuation magnitude (i.e. direct conversion of the g_L-value to decibels, by using Equation (7a), gives a numerically lower result than the use of Equation (7)).

2.2. Equipment arrangement

2.2.1. Generation of luminance fluctuations*

The effect of variations in the exposure of successive film frames on the displayed picture was simulated by varying the intensity of illumination of a transparency in an otherwise conventional optical projector arrangement. This was achieved by illuminating the slide using two light sources (Fig. 3). Light from the direct-path source passed through a semi-reflecting mirror to the transparency, and then by way of a projection lens to the viewing screen. Light from the variable-path source was reflected from the

* The basic design of this equipment was carried out by H.A.S. Philippart and the equipment was constructed by F.H. Brown.

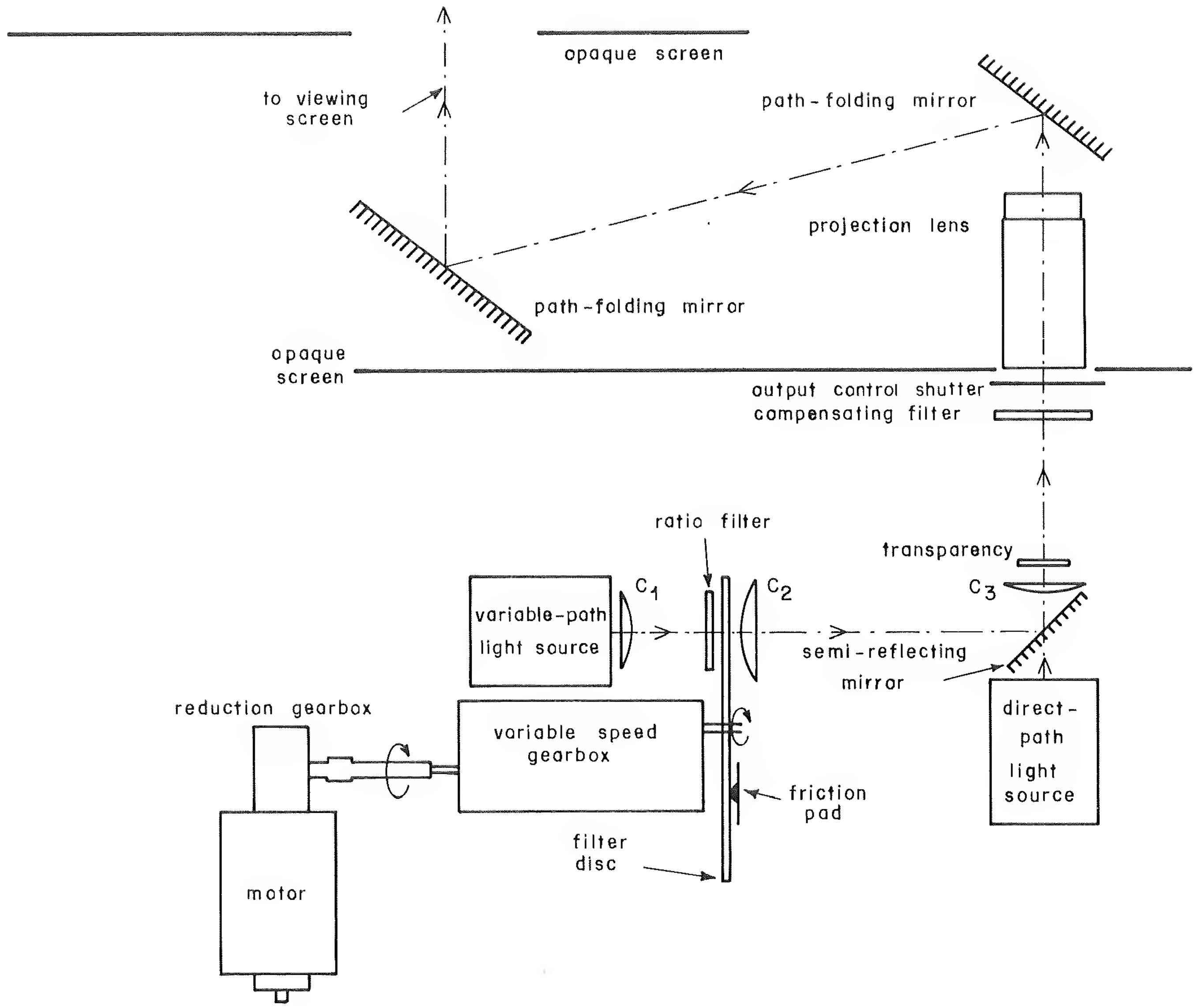


Fig. 3 - Experimental arrangement

C_1 C_2 C_3 : Condenser lenses —·— Optical path ↻ Shaft rotation

semi-reflecting mirror and again passed through the transparency and lens to the screen. Modulation of the intensity of the variable-path illumination was carried out using a rotating transparent disc carrying a graded series of neutral-density filters, a close approach to a raised sinusoidal waveform being realised. The speed of rotation of the filter disc could be varied in discrete steps using a multi-ratio gearbox. Torsional oscillations of the filter disc, which could cause periodic variations of luminance fluctuation frequency, were damped out using a friction pad acting on the disc.

The maximum intensity of the variable-path illumination was controlled by the insertion of one of a set of neutral-density 'ratio' filters into the light path adjacent to the filter disc: these filters were calibrated in terms of the luminance fluctuation ratio (Equation (5)) by measurements of the 'open-gate' (i.e. with the transparency removed) screen luminance using each light source separately. Additional filters could be inserted into the path common to both light sources to compensate for the change in mean luminance with change of luminance fluctuation ratio (Equation (3)), and a shutter was provided to obscure the output from the equipment during changes in the experimental conditions. Condenser lenses were inserted into each light path to obtain adequate optical efficiency (especially from the variable-path source) and freedom from vignetting effects.

The equipment (Fig. 4) was somewhat noisy in operation and emitted a considerable amount of stray light. The experiment was therefore carried out in a small film review room, the equipment being placed in the projection booth. Screens were placed (see Figs. 3 and 4) to intercept all stray light components directed towards the window of the projection booth. Folding of the optical path was required to obtain the correct size of projected picture in the restricted distance between the projection booth and the screen, using a standard projection lens.

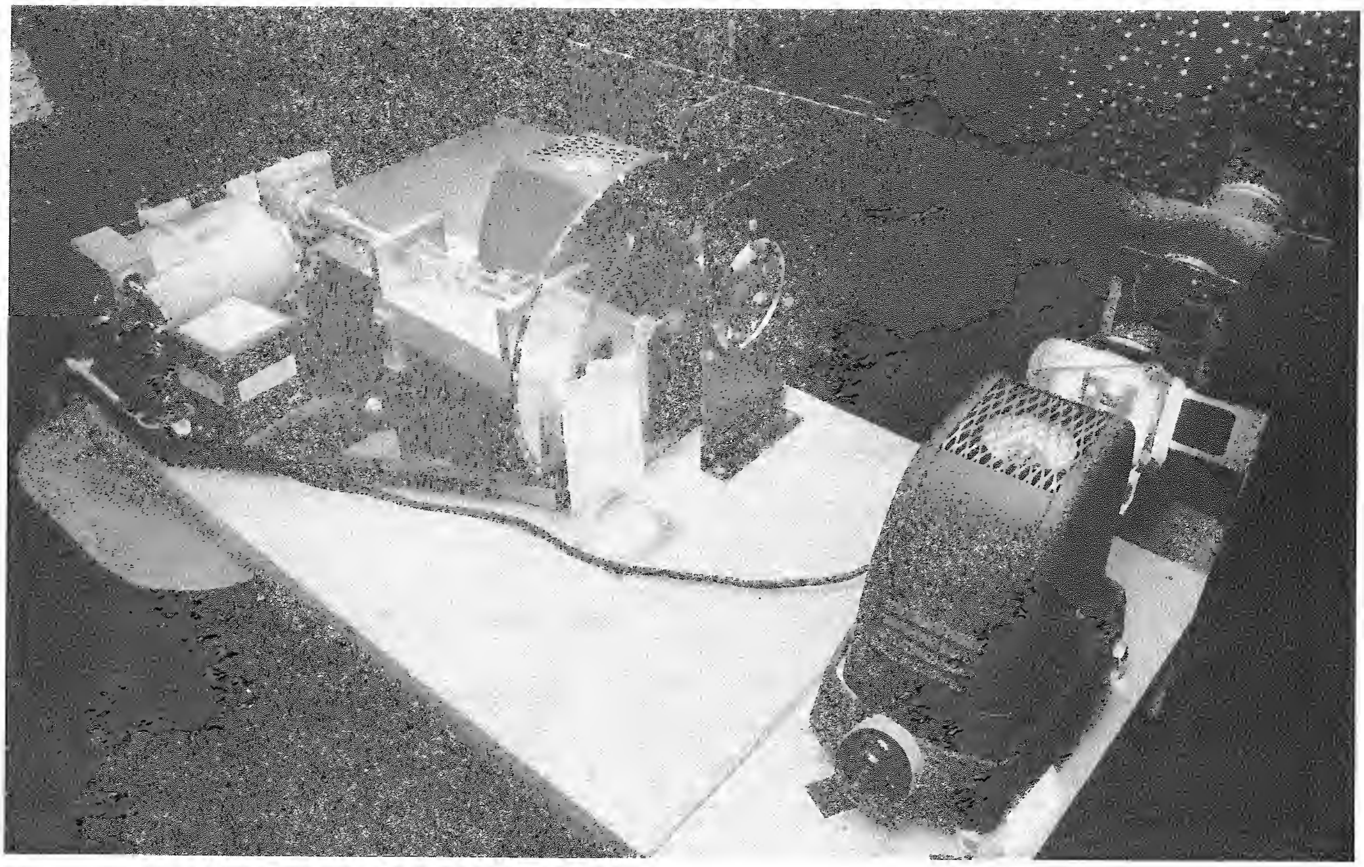


Fig. 4 - Equipment mounted in projection booth

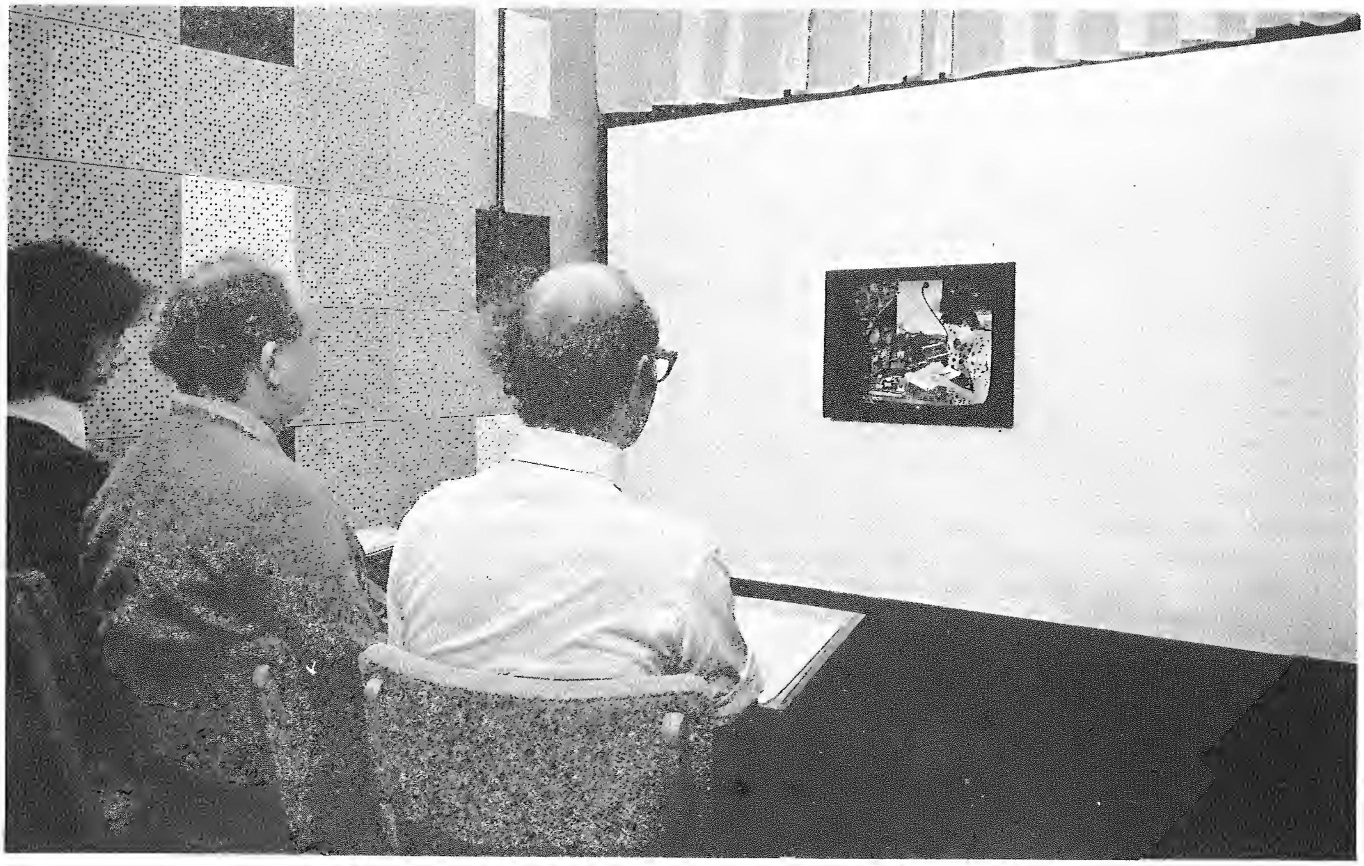


Fig. 5 - Viewing conditions used for tests

2.2.2. Viewing conditions

Viewing conditions (Fig. 5) were as far as possible arranged to comply with the standard conditions[3] recommended for television control rooms. The viewing screen was provided with a black surround shaped to resemble a television display, the peak luminance of the screen in the direction of the observers being within the range 70 ± 10 cd m^{-2} (20·4 ± 2·9 ft-L). Individual transparencies were, where necessary, adjusted using neutral-density filters to maintain this condition. A diffuse white 'background' screen was provided outside the picture area, and a patch of illumination extending at least one picture width horizontally or picture height vertically was thrown onto this screen using a small auxiliary projector. The luminance of this patch was approximately 7 cd m^{-2} (2 ft-L). The auxiliary projector was provided with an opaque stop in the plane normally occupied by the transparency, which prevented the background illumination from falling onto the viewing screen. Illumination from other room lighting was maintained at a low level, and the luminance of the viewing screen in the absence of the projected picture was less than 0·7 cd m^{-2} (0·2 ft-L): achievement of this low value was made possible by the use of directional viewing-screen material.

There was insufficient light output from the projection equipment to enable the chromaticity of picture white to be corrected to D_{65} (the standard white-point chromaticity of television displays), and the white-point of the projected pictures was therefore approximately 3000 K. The background illumination was of a similar chromaticity. A change in chromaticity from P_{3000} to D_{65} is not likely[4a,5a] to have any effect on the visibility of luminance fluctuations of television displays, and the results obtained using this equipment are therefore directly applicable to the viewing of television pictures.

The observers taking part in the tests were seated, four* at a time, at a distance of six times the picture height from the viewing screen. A panel of fifteen observers was used, any one test condition being assessed by twelve observers. All the observers were familiar with subjective test procedures, and about half of them were directly concerned with colour television engineering. The observers returned their assessments using the six-point impairment scale shown in Table 1.

TABLE 1

Scale of Subjective Impairments

Grade	Description
1	Imperceptible
2	Just perceptible
3	Definitely perceptible but not disturbing
4	Somewhat objectionable
5	Definitely objectionable
6	Unusable

* To illustrate the viewing conditions with greater clarity, only three observers appear in Fig. 5.

Slide P

Slide Q

Slide R

Fig. 6 - Black-and-white reproductions of pictures used during tests

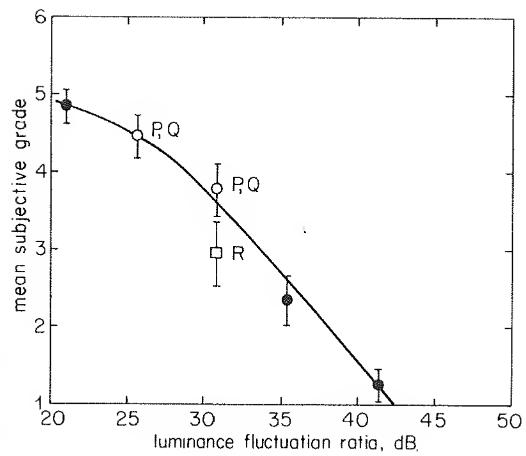


Fig. 7 - Fluctuation frequency 9·56 Hz

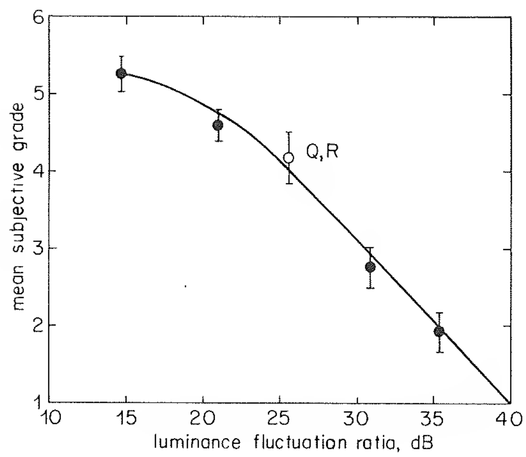


Fig. 8 - Fluctuation frequency 4·3 Hz

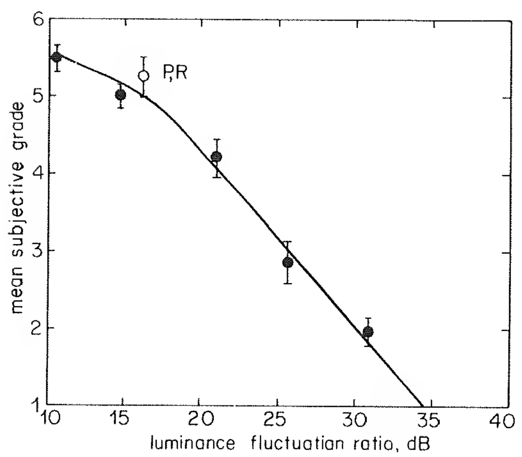


Fig. 9 - Fluctuation frequency 2·15 Hz

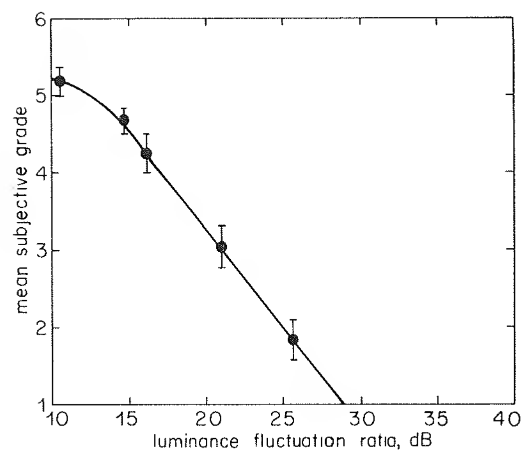


Fig. 10 - Fluctuation frequency 1·08 Hz

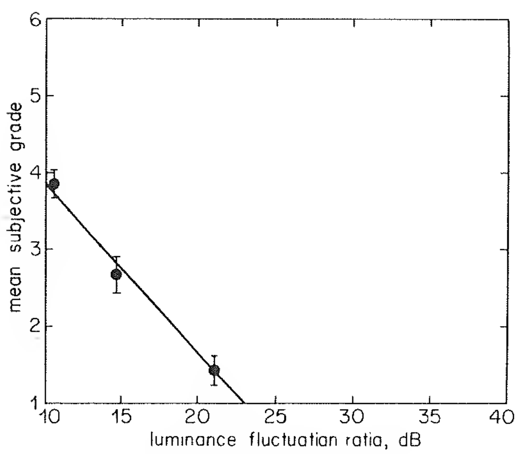


Fig. 11 - Fluctuation frequency 0·43 Hz

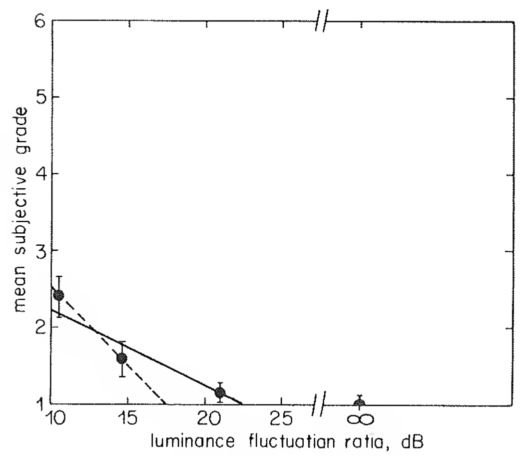


Fig. 12 - Fluctuation frequency 0·21 Hz

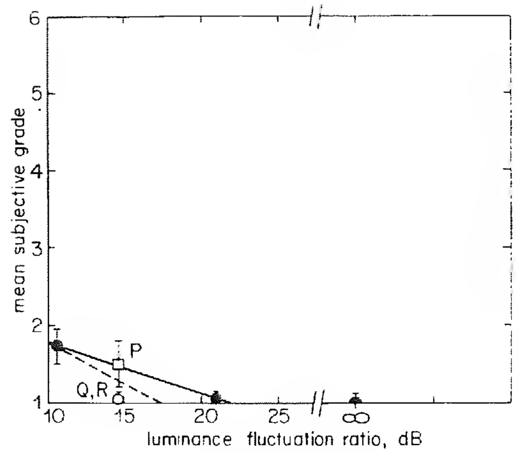
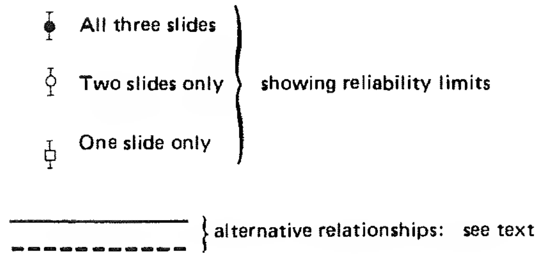


Fig. 13 - Fluctuation frequency 0·11 Hz

Figs. 7 — 13 - Relations between luminance fluctuation ratio and mean subjective grade



Because of the possibility of progressive contamination of the optical surfaces in the direct and variable light paths (particularly the inside surface of each lamp, due to filament evaporation), there was the chance of a continuous 'drift' of equipment calibration during the course of the tests. The equipment was therefore calibrated both before and after the tests, and the mean value of these calibrations was adopted in calculating the luminance fluctuation ratio values. Since the occasions on which individual observers assessed a given test condition were distributed in a random manner throughout the series of tests, any progressive change in the calibration of the equipment would act to increase the scatter of all the assessments (see Section 2.3) rather than affect the relative assessment of individual test conditions. Similarly, a progressive change in observers' opinion during the tests would also tend to increase the scatter of all the assessments, rather than introduce a shift in mean grade value for some test conditions relative to others (although it must be emphasised that this procedure could not act to eliminate the overall effect of such a change of opinion on the results of the tests).

When carrying out a series of subjective tests it must be remembered that some features in the displayed picture may tend to mask the effects under evaluation. In the present case it was considered important to avoid such features as far as possible, since a very critical assessment of the luminance fluctuation effects was required (see Section 4.1). The use of still pictures avoided any masking of the luminance fluctuation effects by picture movement. Direct optical projection eliminated the flicker effects associated (particularly when peripheral vision is involved[4b]) with television displays having a 50 Hz field frequency, and which could have been confused with some of the effects under consideration. Each combination of luminance fluctuation magnitude and frequency was assessed using three displayed colour pictures (Fig. 6), which differed in the amount of picture detail present, although it was in fact found (see Section 3.1) that this factor was largely insignificant in determining the visibility of the luminance fluctuation effects.

2.3. Method of analysis

The analysis of the results of the subjective tests has been carried out in terms of the mean grade value returned by the observers for each test condition. The assessment of the degree of reliability of each of the mean values, and of the significance of the difference between two mean values, has been based on the proposition[6a] that, given a set of quantities having a normal statistical distribution, the probability that an individual quantity will differ from the mean quantity value by more than twice the standard deviation is approximately 5%. As far as the mean grade values are concerned, the standard error (ϵ), given by

$$\epsilon = \frac{\sigma}{\sqrt{N}} \tag{8}$$

where σ is the standard deviation

and N is the number of individual assessments contributing to the mean grade value,

has been taken[6b] as being equal to the value of standard deviation of the mean grade values (i.e. the standard deviation of the set of mean values that would have been obtained if the experiment had been repeated a large number of times). There is thus a 95% probability that a mean grade value would, if the experiment was repeated, fall in the range $\pm 2\epsilon$ about the calculated mean value, and this criterion has therefore been used to derive the reliability limits shown in Figs. 7 — 14.

The test as to whether or not the difference between two mean grade values is significant has been based on the assumption[6c] that the variance* of the difference between the two mean values is the sum of the individual variances of each value. If ϵ_D is (using terminology appropriate to the present case) the standard error associated with the difference between the two mean values, then

$$\epsilon_D = \sqrt{\epsilon_A^2 + \epsilon_B^2} \tag{9}$$

where ϵ_A and ϵ_B are the standard errors of the individual means.

* i.e. the square of the standard error, in the present case.

In the present case these tests of significance have been carried out between the individual members of sets of three mean values having identical conditions of luminance fluctuation frequency and ratio, but differing in the displayed picture used during the tests, and a simplified method of determining the standard error value to be used in the test of significance has been used. An 'average' standard error (ϵ_{av}) over the three mean grade values was first calculated, given by

$$\epsilon_{av} = \sqrt{\frac{\epsilon_1{}^2 + \epsilon_2{}^2 + \epsilon_3{}^2}{3}} \qquad (10)$$

where ϵ_1, ϵ_2 and ϵ_3 are the standard errors for the three mean grade values under consideration.

This average standard error value was then taken as applying to each of the mean grade values: thus Equation (9) reduced to

$$\epsilon_D = \sqrt{2}.\epsilon_{av} \qquad (11)$$

and two mean grade values were considered significantly different only if this difference exceeded $2\epsilon_D$ (i.e. there was a less than 5% probability of such a difference occurring purely by chance). Furthermore, a set of mean grade values was not regarded as containing significantly different individual values unless, at the least, one value differed significantly from both the others (in fact, no case occurred in which all three values differed significantly from each other).

Because of the small number of observers taking part in the tests, the above analytical procedure can only be regarded as giving an approximate indication of the significance of the test results. It is however generally accepted[6d] that this procedure does give a reasonable indication of this significance.

An estimate has also been made of the reliability limits associated with the nominal values of luminance fluctuation ratio. For the same experimental conditions (in fact, with the ratio filter (Fig. 3) not present) measurements of L_D and L_V (see Equations (1) and (2)) were made at different points in the picture area both before and after the programme of subjective tests. From these measurements a set of luminance fluctuation ratio values were calculated. Treating these observed values as random samples of the ratio values present over the picture, and assuming that the nominal ratio value was given by the mean of these values, the application of the statistical procedure outlined above (Equation (8)) led to the reliability limits of ±1 dB shown in Fig. 14.

During the tests the observers were asked to indicate whether or not the luminance fluctuations were more noticeable in particular areas of the picture. In 89% of the assessments no such distinction was made, but of the remaining assessments there was some indication that the selected picture areas correlated with low luminance fluctuation ratio values. This implies that the adoption of the mean luminance fluctuation ratio as the nominal value, as discussed above, may lead to an overestimate of the ratio value actually perceived by the observer during the tests. The magnitude of this overestimate is not greater than 1·5 dB (i.e. the true ratio value might possibly be 0·5 dB below the negative reliability limit). Since this uncertainty in value is in the direction of conferring an extra 'safety margin' to the results (see Section 4.1) the use of the mean ratio values has been retained in expressing the results of the tests.

3. Experimentally-derived relationships

3.1. Relationships between luminance fluctuation ratio and mean grade

The experimentally-derived relationships between luminance fluctuation ratio (see Equation (5), Section 2.1) and mean subjective grade are shown, for each luminance fluctuation frequency used, in Figs. 7 – 13. In most cases the choice of displayed picture made no significant difference (see Section 2.3) to the mean grade value obtained for otherwise identical test conditions: when this has occurred the mean grade value shown is the average of the results obtained with each picture. Such average results are shown as full circles. The reliability limits, shown by vertical lines, are based on standard error values taken over all 36 observations (i.e. 12 observations per picture and three pictures). In two cases (see Figs. 7 and 13) the results obtained for one picture differed significantly from those obtained using the other two pictures, these latter results not differing significantly from each other. These results are shown by open squares and open circles respectively, the corresponding standard error values being taken over 12 and 24 observations. The particular pictures in question are also indicated (see Fig. 6). In three further cases (see Figs. 7, 8 and 9) an error in the test schedules resulted in the omission of one displayed picture: the results obtained for the two remaining pictures did not differ significantly and the mean of these results is again shown by open circles. None of these three points critically affect the derivation of the ratio-limit curves (Figs. 14 – 16). In no case did the results using each of the three pictures differ significantly from each other.

With the exception of the two lowest luminance fluctuation frequencies, it was found possible to draw unambiguous straight-line relationships which fell within the reliability limits of all the experimental results for which a mean grade value of below about 3·5 was returned. For higher mean grade values there was some reduction in the rate of increase of grade value with decrease in luminance fluctuation ratio. The slope of the straight-line portions of these relationships was very similar, having a mean value of 4·4 dB per grade. This result is interesting as it agrees reasonably closely with the value of 5 dB per grade obtained by Geddes[7] for television picture impairments due to random noise.

In the case of the two lowest luminance fluctuation frequencies (Figs. 12 and 13) the restricted range of luminance fluctuation ratios over which the fluctuations were visible, combined with the scatter of the experimental

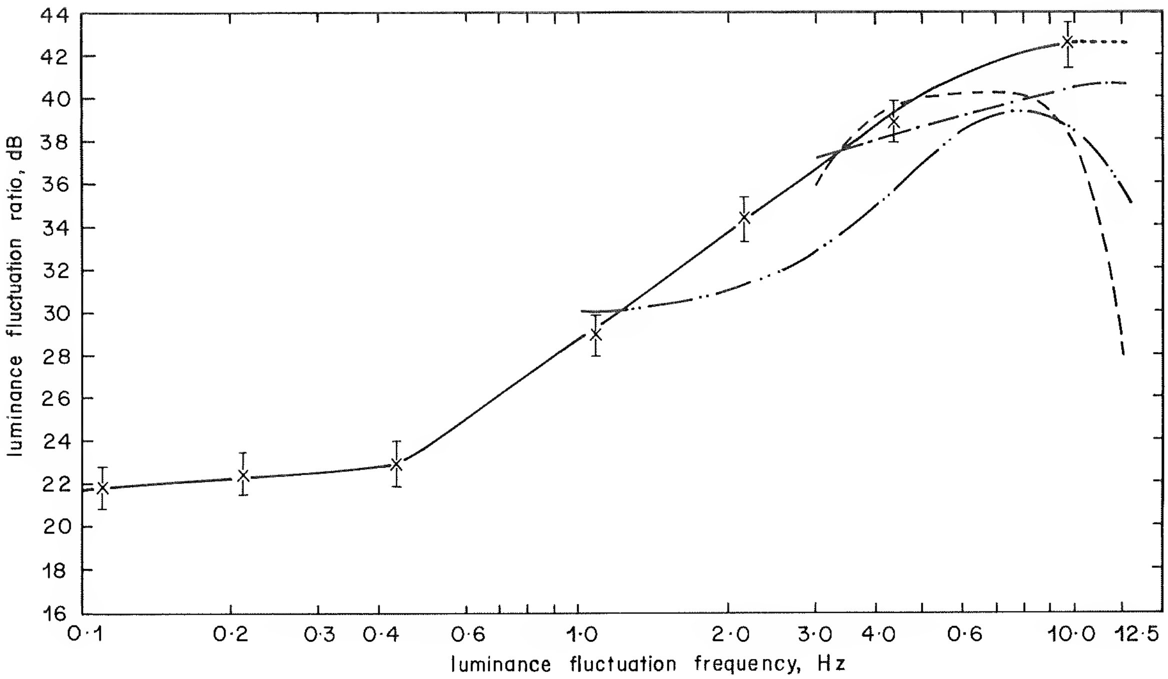


Fig. 14 - Relationship between luminance fluctuation ratio and fluctuation frequency for a mean subjective grade of unity

——— •••••present investigation, showing extrapolation — — — — Dow, 1907 ••—••—•— Dzn, 1958 —•—•—•— Taylor, 1962

results, led to some ambiguity in the determination of the relationship between the ratio value and the mean subjective grade. The full and dotted lines in Figs. 12 and 13 represent possible extreme cases of this relationship (the dotted lines can be justified on the grounds that the mean grade values obtained for a luminance fluctuation ratio value of 21 dB were in neither case significantly different from the grade value (see points at '∞ dB') obtained with no luminance fluctuation present). In the derivation of the relationship between luminance fluctuation ratio and frequency (Section 3.2) the full-line relationships shown in Figs. 12 and 13 have been used as representing the 'worst case' condition and therefore relevant in the determination of luminance fluctuation ratio limits (Section 4).

3.2. Relationship between luminance fluctuation ratio and frequency, for a given mean grade

Figs. 7 — 13 enable the luminance fluctuation ratio value for any given subjective grade criterion to be obtained at each of the fluctuation frequencies used during the tests. These ratio values, for a mean subjective grade value of unity, are shown in Fig. 14. The derivation of the reliability limits of ±1 dB on the ratio values has been discussed in Section 2.3. The ratio values for fluctuation frequencies of 0·21 Hz and 0·11 Hz correspond to the full-line relationships in Figs. 12 and 13 as discussed in Section 3.1.

The relationship between fluctuation frequency and luminance fluctuation ratio required for a mean grade of unity may, within the experimental reliability limits, be represented over the frequency range of 0·5—5·0 Hz by a straight line. This linear relationship is obtained using a logarithmic frequency-axis scale. At higher and lower frequencies the gradient of this line decreases. Other work (see below) indicates that the required luminance fluctuation ratio would be expected to decrease for frequencies significantly higher than those covered by the present investigation. In the present case the highest frequency of interest is 12·5 Hz (see Section 1): it is reasonable to assume that the same ratio value applies to this value as to a frequency of 9·56 Hz (dotted line in Fig. 14).

It is interesting to compare the results discussed above with those obtained by other methods. Dow[8,4c] obtained results over the range 3—12·5 Hz, for several different luminance values of the field of view. His work was concerned with photometry and is expressed in terms of the incident illumination rather than the field-of-view luminance: however, Walsh[4c] has expressed these results in terms of field luminance (in units of retinal illumination: see Appendix I) and the highest luminance value in Dow's results (approximately 6 cdm^{-2} (1·7 ft-L)) has been taken in this comparison. These results refer to the 'smallest detectable' change of luminance: taking this as being equivalent to Grade 2 (Table 1), 4·4 dB has been added (see Section 3.1) to the luminance fluctuation ratio values calculated from the original results to adapt this criterion to the present case of a mean grade of unity. This comparison is shown by the dashed line in Fig. 14.

More recently de Lange Dzn[9] has obtained results again including a range of field-of-view luminance* for two observers (Figs. 5 and 6 of Ref. 9) over a wide frequency range, commencing at 1·0 Hz. His results are in terms of 'no longer visible' luminance changes: taking this as equivalent to Grade 1 in Table 1, no correction is needed to the

* also expressed in terms of retinal illumination.

luminance fluctuation ratios calculated from the original results. The double chain-dotted line in Fig. 14 shows the mean of the ratios calculated for each of Dzn's observers, with a field-of-view luminance of approximately 7 cd m^{-2} (2 ft-L).

Work carried out by the present author on television co-channel interference[10] included the effect of very low frequency differences (down to about three hertz) between the carriers of the wanted and interfering transmissions. The conversion of the co-channel interference results into terms comparable with the present investigation is described in Appendix II, and these converted results are shown in Fig. 14 by the chain-dotted line.

In spite of the very different experimental conditions and subjective criteria used in these different investigations, there appears to be a very considerable measure of agreement between the various sets of results shown in Fig. 14 over the frequency ranges for which the results were obtained. The shapes of the curves suggest, however, that extrapolation of these earlier relationships might have led to considerably different results than those obtained in the present work.

It may be noted that Dzn's work indicates that the luminance fluctuation ratio required to render the fluctuations imperceptible does not appear to increase greatly, over the frequency range of 1·0—10·0 Hz, as the field-of-view luminance is increased beyond the value for which the above comparisons have been made. At a frequency of 10 Hz, for example, an increase in retinal illumination by a factor of ten leads to corresponding increases in luminance fluctuation ratio values of 1·3 dB and 4·6 dB for Dzn's two observers, while a further tenfold increase in retinal illumination leads to no further increase in the required ratio value. At lower frequencies a smaller increase in the ratio value is in general required under these conditions. These factors indicate that the present relationship shown by the full line in Fig. 14 may be applied to displays having luminances higher than 70 cd m^{-2} (20·4 ft-L).

A further point of interest lies in the luminance fluctuation frequency at which the greatest ratio value is required to render the fluctuations imperceptible. Both Dow and Dzn show a maximum value in the region of 7—8 Hz, while the co-channel interference results indicated a maximum at approximately 12 Hz. Although the relationship drawn for the present results implies a maximum somewhat higher in frequency than 10 Hz (i.e. agreeing with the co-channel interference work) it would be equally plausible to draw this relationship through the experimental points so as to show a maximum in the 7—8 Hz region. This procedure would not, however, lead to a maximum ratio value significantly greater than is at present shown for frequencies of 10—12·5 Hz, and thus would not greatly affect the recommendations on luminance fluctuation ratio limits given in Section 4 below.

4. Recommended luminance fluctuation ratio limits

4.1. Allowance for observers sensitive to luminance fluctuation effects

The relationship shown in Fig. 14 refers to luminance fluctuation ratio values required to obtain a mean subjective grade of unity. The use of the mean grade value implies that there will be a number of observers, more sensitive to luminance fluctuations than average, who would perceive luminance fluctuations for such ratio values. In determining a recommended limit to the ratio values, allowance must be made for these more sensitive observers so that over the viewing public as a whole very few people (ideally none at all) will perceive luminance fluctuations for ratio values greater than this limit. In principle, the statistical methods discussed in Section 2.3 could be used for this purpose: for example, it would be possible to calculate a mean value of the standard deviation of the test subjects' results, and then add a multiple of this standard deviation, corresponding to a suitably low probability value (say 0·1%), to the mean grade values to obtain values which notionally include the majority of viewers (99·95% in the above example). However, although the use of such methods is likely to give a meaningful assessment of the experimental accuracy achieved during the tests, it is not likely to give a realistic indication of the behaviour of the viewing public as a whole unless it is assumed that the distribution of the observers' results corresponds with some precision with that of the viewing public. Since this assumption cannot be made, in view of the relatively small number of observers used during the tests, the cruder but possibly more realistic statistical treatment outlined below has been adopted.

For convenience in carrying out the subjective tests the test conditions were divided, in a random manner, into four 'sessions'. A total of twelve observers took part in any one session. For each session, the mean of all the subjective grade values returned by each observer was calculated, and a 'grand mean' of all these individual mean values was taken.* The difference between the grand mean and the mean for each individual observer was then taken, again for each session. It was found that some observers consistently returned a mean grade value, through all the test sessions, which was higher than the corresponding grand mean, while other observers similarly returned a consistently low value. Regarding the first category of observers as those showing greater than usual sensitivity to luminance fluctuation effects, the largest value by which a sensitive observer's mean grade exceeded the grand mean was 0·6. Since (see Section 3.1) the average value of the slope of the relationships between luminance fluctuation ratio and mean grade was found to be 4·4 dB per grade, the value of 0·6 grade corresponds to a ratio value of 2·7 dB. Thus it may be postulated that an increase in luminance fluctuation ratio of 2·7 dB over and above the value obtained for a mean subjective grade of unity should render the luminance fluctuations imperceptible to the most critical of the observers taking part in the tests. While it is open to argument

* The grand mean values for the four sessions were equal to within a quarter of a grade, indicating the uniformity of the distribution of different test conditions between the sessions.

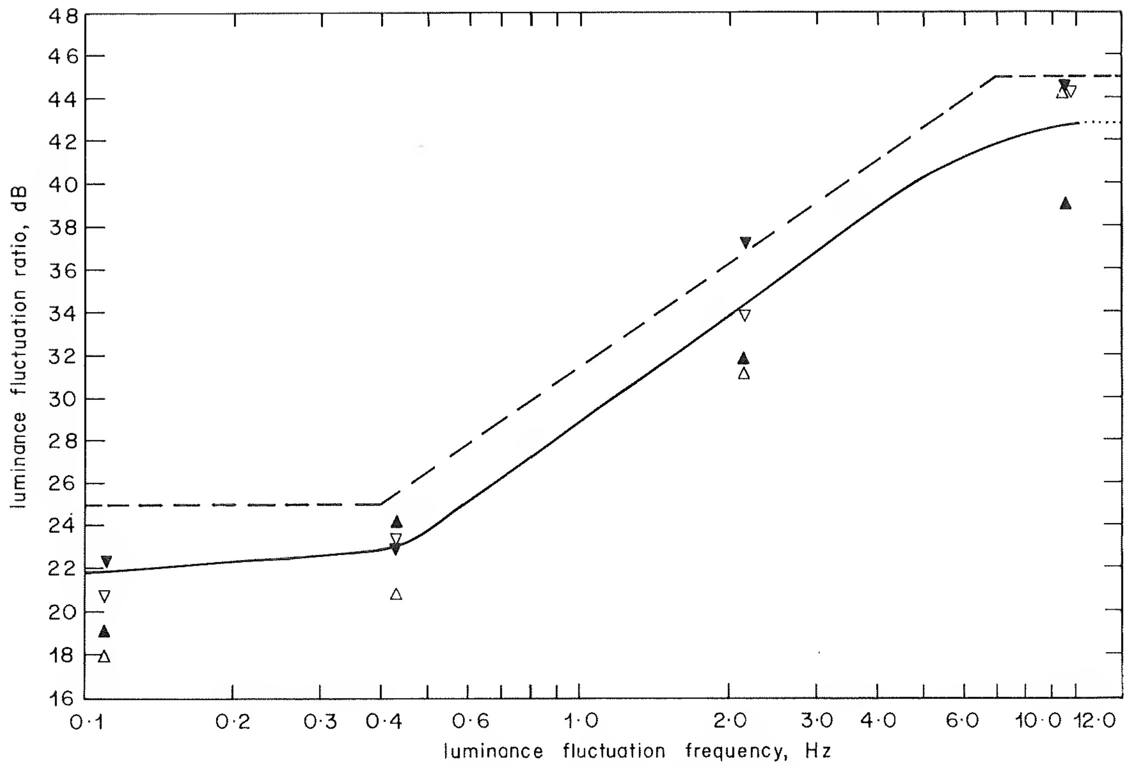


Fig. 15 - Recommended limit on permissible luminance fluctuation ratios, showing results of confirmatory experiment

——————•••••••experimental result, with extrapolation (see Fig. 14) - - - - - - - - recommended limit

▲ and ▼ confirmatory experiment : two most sensitive observers △ and ▽ confirmatory experiment : two other observers

whether a luminance fluctuation ratio limit based on this criterion would render the luminance fluctuations imperceptible to all members of the viewing public, it is felt that it represents the best compromise between ensuring the imperceptibility of the fluctuations on the one hand, and not specifying too rigid a tolerance on the other hand, that can be deduced from the experimental results. This limit is shown as a function of fluctuation frequency by the dashed line in Fig. 15. It can be seen by comparison with the experimentally-derived relationship (full line in Fig. 15) that the limit relationship has been 'idealised' to a number of straight lines, and further that the frequencies at which discontinuities in the relationship occur have been 'rounded off' to 0·4 Hz and 7·0 Hz.

If a linear relationship exists between relative film exposure and resulting relative picture luminance, the dashed line in Fig. 15 also represents the limit which must be placed on exposure variations* in order to avoid the appearance of luminance fluctuations on the displayed picture (see dashed line in Fig. 16). If this relationship is non-linear a more stringent limit must be placed on the exposure variations. This aspect is discussed in Section 4.3.

4.2. Experimental verification of recommended limits

The experimental arrangement for testing the validity of the luminance fluctuation ratio limits discussed in Section 4.1 was basically the same as was used for the main series of tests. The size of screen was reduced to one-third of the original linear dimensions, so that little ambiguity in the value of luminance fluctuation ratio occurred over the screen surface. One observer sat at a distance such that the screen subtended an angle equivalent to half of the original picture dimensions. The screen was again provided with a black surround which was in turn surrounded with an area of background illumination (see Section 2.2.2). A blue (colour-temperature raising) filter was placed in the gate of the projection system instead of a colour transparency: the filter was arranged to give a screen luminance of 70 cd m^{-2} (20 ft-L) and the resulting colour temperature was 4800K. The screen colour therefore corresponded more closely to the white-point of a television display than was the case during the main series of tests. The chromaticity of the background illumination was similarly adjusted. The observer was provided with a push-button for indicating whether or not the luminance fluctuations were visible, and the test supervisor adjusted the value of ratio filter to achieve the greatest transmission in the variable path consistent with imperceptibility* of the fluctuations. For this purpose a number of uncalibrated filters of low density were provided so that the luminance fluctuation ratio could be varied in steps of less than 1 dB, and measurements of L_D and L_V (Equations (1) and (2)) were made after the completion of each test condition.

* Units of exposure variation are defined in Equations 13 – 16 (Section 4.3).

* as shown by lack of correlation between the operation of the observer's push-button and the intermittent obscuration of the variable light path using a shutter over the condenser lens C_2 (Fig. 3).

The values of luminance fluctuation ratio obtained in this way from four observers (including the two judged to be most sensitive to luminance fluctuations, as discussed in Section 4.1), at four fluctuation frequencies, are shown by the points in Fig. 15. One sensitive observer required a marginally greater luminance fluctuation ratio value for rendering the fluctuations imperceptible at a frequency of 2·15 Hz, but in general the relationship between ratio value and frequency recommended in Section 4.1 (dashed line in Fig. 15) is confirmed, at least for the observers taking part in the tests. In fact there are indications that for very low fluctuation frequencies the recommended relationship is excessively stringent: nevertheless, it seems advisable to retain this relationship unless further evidence indicates that a relaxation in the proposed limits on luminance fluctuation ratio is possible.

4.3. Allowance for a non-linear transfer characteristic

Nominally the luminance of an area of a television display is proportional to the luminance of the corresponding scene area. It is, however, almost universal present-day practice for the television transmission chain to have a non-linear overall transfer characteristic obeying, at least approximately, the relationship

$$L_{out} = kL_{in}{}^{\gamma} \tag{12}$$

where L_{out} is the output (display) luminance

L_{in} is the corresponding input (scene) luminance

and k and γ are constants for particular video – signal processing parameters and display adjustments, the value of γ being greater than unity.

This relationship applies to all television transmissions, whether or not the use of film is included. In the present context the effect of cyclic variations of film exposure is under consideration and the use of film is therefore implicit. Since film exposure is proportional to scene luminance, variations in exposure may be considered in terms of equivalent variations in scene luminance, even though, as in the present case, the exposure variations are not in fact produced directly by scene luminance changes.* New quantities relating to variations in exposure may therefore be defined which are directly analogous to the quantities already used to express the magnitudes of luminance variations (see Equations (4) – (7a)) except that they refer to exposure rather than to luminance values. Thus by analogy with Equation (4) the 'normalised exposure difference' (D_E) is given by

$$D_E = \frac{E_{max} - E_{min}}{E_{mean}} \tag{13}$$

* i.e. changes in average scene luminance, for example as observed visually. The scene luminance is in fact fluctuating at twice the supply frequency (see Section 1), but fluctuation at this rate is not ordinarily visible unless shown up by strobing effects with rapidly moving objects.

where E_{max}, E_{min} and E_{mean} are the maximum, minimum and mean exposure values respectively.

Similarly the 'exposure fluctuation ratio' (R_E dB) is by analogy with Equation (5) given by

$$R_E = 20 \log_{10} \frac{1}{D_E} \tag{14}$$

The ratio of the maximum and minimum exposure values (M_E) is by analogy with Equation (6) given by

$$M_E = \frac{E_{max}}{E_{min}} \tag{15}$$

while, if

$$M_E = 1 + g_E, \quad (1 \leqslant M_E < 2)$$

a process analogous with the derivation of Equations (7) and (7a) gives

$$R_E = 20 \log_{10} \frac{2 + g_E}{2g_E} \tag{16}$$

$$= 20 \log_{10} \frac{1}{g_E}, \quad (g_E \ll 1) \tag{16a}$$

For a television system* involving the use of film, Equation (12) may therefore be re-written

$$L = kE^{\gamma} \tag{17}$$

where E is the film exposure corresponding to the output (display) luminance L.

It can be seen by differentiating Equation (17) that

$$dL = \gamma k E^{\gamma-1} \; dE \tag{18}$$

and by dividing Equation (18) by Equation (17) and replacing the differential operators by the small but finite differences ΔL and ΔE

$$\frac{\Delta L}{L} = \gamma \frac{\Delta E}{E} \tag{19}$$

Now it is evident from Equation (13) that

$$\frac{\Delta E}{E} = D_E \tag{20}$$

where D_E is the normalised exposure difference.

* Note that since film usually has a non-linear transfer characteristic the argument which follows applies to the direct optical projection of film as well as its use in a television system.

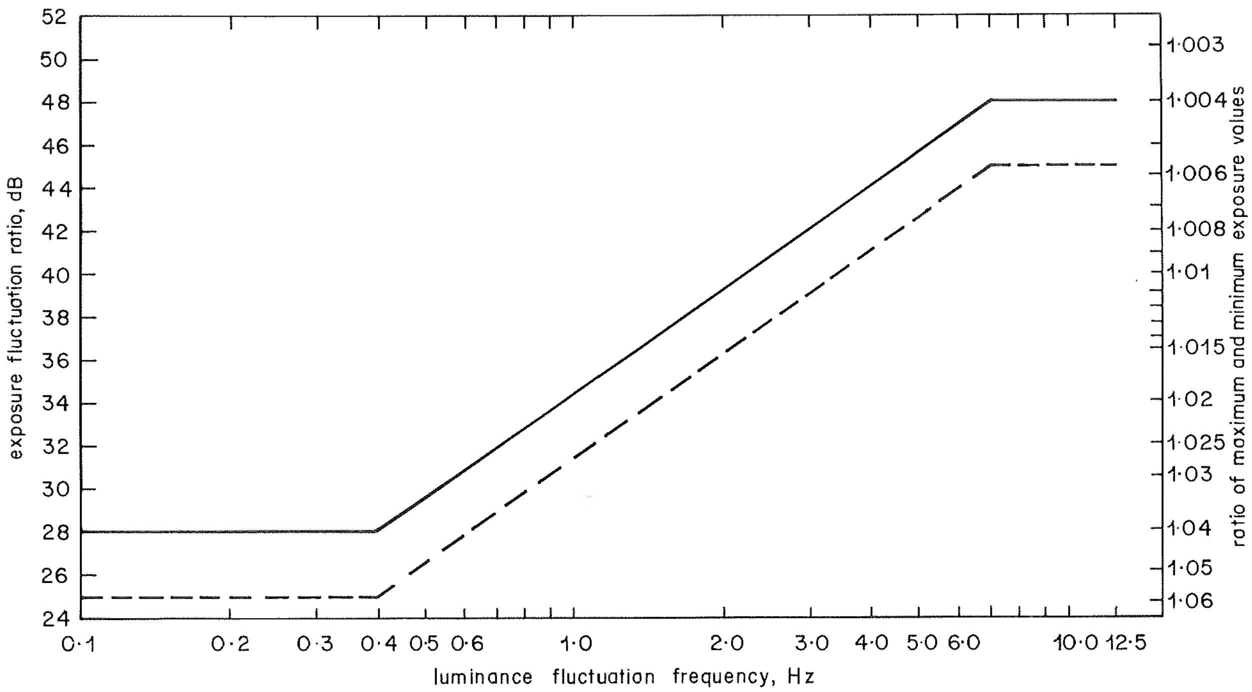


Fig. 16 - Recommended limit on permissible exposure variations

- - - - - - - - linear transfer characteristic ———— non-linear transfer characteristic; $\gamma = 1{\cdot}5$

Similarly from Equation (4)

$$\frac{\Delta L}{L} = D_{\mathrm{L}} \tag{21}$$

where D_{L} is the normalised luminance difference which would be obtained using the non-linear transfer characteristic defined by Equation (17).

It can therefore be seen by substituting Equations (20) and (21) into Equation (19) that

$$D_{\mathrm{L}} = \gamma D_{\mathrm{E}} \tag{22}$$

Equation (22) can be expressed in terms of luminance fluctuation ratio values as

$$R_{\mathrm{E}} = R_{\mathrm{L}} + 20 \log_{10}\gamma \tag{23}$$

where R_{E} and R_{L} are related to D_{E} and D_{L} by Equations (14) and (5) respectively. Equation (18) shows that the exposure fluctuation ratio (R_{E}) must be numerically greater than the luminance fluctuation ratio (R_{L}) appearing on the displayed picture by an amount depending on the value of γ. As the limits of luminance fluctuation ratio value recommended in Section 4.1 for a linear system (dashed line in Fig. 15) refer to the values appearing on the displayed picture, the corresponding exposure fluctuation ratio limits must be numerically greater by this same gamma-dependent amount. In order to assign a definite value to this amount, it may be noted[11] that the value of γ can be as high as 1·5 when film material is used in a television system. The use of this gamma value admittedly represents a 'worst case' criterion, but is adopted to provide an additional safety margin (see Section 4.1). This should further ensure that very few of the viewing public will be aware of luminance fluctuations caused by exposure fluctuation ratio values greater than the recommended limits. For a gamma value of 1·5 the last term in Equation (23) takes the value 3·5. However, since the value of γ usually decreases towards the high picture-luminance end of the transfer characteristic, it seems reasonable to write Equation (23) for this case as

$$R_{\mathrm{E}} = R_{\mathrm{L}} + 3 \tag{24}$$

This relationship is shown by the full line in Fig. 16 and represents the final recommended limit on the permissible exposure variations of film to be used in a television transmission system. For convenience, the exposure variations are expressed in terms of the ratio of the maximum and minimum exposure values (see Equations (15) and (16)) as well as in exposure fluctuation ratio units (Equation (14)).

In making use of the relationships shown in Fig. 16, it should be remembered (see Section 1) that the fluctuations of luminance on a television or directly-projected film display are caused by the presentation of a succession of differently-exposed film frames at a rate, in the present case, of 25 per second. If the cycle of exposure variation is of relatively long duration relative to 1/25 second, and therefore occurs over many film frames, the resulting fluctuation of display luminance will be of an approximately sinusoidal character and the relationships shown in Fig. 16 are directly applicable. If, on the other hand, this cycle is of shorter duration, only a few film frames are involved in each cycle. This will give rise to two effects.

The first effect of a short exposure cycle is that the fluctuation of display luminance will be markedly non-

sinusoidal in character. Allowance can be made for this effect, since it has been shown[9] that the sensitivity of the eye to luminance fluctuations falls off rapidly for fluctuation frequencies greater than about 15 Hz: thus only the fundamental component of the display luminance fluctuation will be effective in determining its visibility.

The second and more important effect that can occur in a short exposure cycle is that the magnitude of the exposure variations can depend on the time relationship between the two effects described in Section 1 (i.e. film exposure interval and illumination ripple waveform). For example, if the camera frame frequency is such that alternate film frames could receive different exposures (giving rise, on replay, to a display luminance fluctuation frequency of 12·5 Hz), the situation can arise in which two different samples of illumination ripple waveform, defined by alternate film exposure intervals, nevertheless give rise to equal film exposures: thus in this case no luminance fluctuations would be observed. An alteration in the timing of the film exposure interval relative to the illumination ripple waveform can destroy this equality of alternate film exposures, resulting in the appearance of luminance fluctuations.* If the camera frame frequency is not simply related to the lamp supply frequency, so that the above-discussed time relationship is continually changing, the relatively rapid fluctuations in display luminance will, in effect, be modulated in magnitude by a component of lower frequency, causing the periodic appearance and disappearance of the display luminance fluctuations. Furthermore, the frequency of the rapidly-fluctuating component may differ from the frequency calculated simply from knowledge of the lamp supply and camera frame frequencies. These factors must be taken into account when determining the appropriate limit of film exposure variation. However, it may be noted that in practice, for camera frame and lamp supply frequencies having nominal values of 25 Hz and 50 Hz respectively, the luminance fluctuation frequency is likely to be low enough to enable the relationships shown in Fig. 16 to be directly applicable.

5. Conclusions

The magnitude of the fluctuations in luminance of a displayed picture required to render these fluctuations imperceptible depends markedly on the frequency of the fluctuations. For fluctuations obeying a sinusoidal time function, the luminance fluctuation ratio (see Equations (4) and (5)) required for imperceptibility of the fluctuations varied from 25 dB for frequencies of 0·4 Hz and below to 45 dB for frequencies in the range 7 – 12·5 Hz.

In a non-linear system such as a television transmission channel, having a power-low transfer function (see Equation (12)) with a 'gamma' value of 1·5, the magnitude of the luminance fluctuations appearing on the display is enhanced, relative to the fluctuations at the input to the channel, to the extent of reducing* the ratio value by three decibels. Thus the input fluctuations must be correspondingly reduced to ensure the imperceptibility of the luminance fluctuations on viewers' screens. If the transmission system involves the use of motion-picture film, cyclic variations in the exposure of successive film frames will give rise to these luminance fluctuation effects. Variations in film exposure may be considered as being caused by equivalent variations in the original scene luminance, even though the exposure variations are not in fact produced directly by scene luminance changes (see footnote on page 12). The exposure-limit relation shown by the full line in Fig. 16 is obtained by using this equivalence between scene luminance and exposure variation, and taking the effect of an overall gamma value of 1·5 into account. Fig. 16 shows that the limits in exposure fluctuation ratio (see Equations (13) and (14)) run from 28 dB for frequencies of 0·4 Hz and below to 48 dB for frequencies in the range 7 – 12·5 Hz. The corresponding permissible values of the ratio of maximum to minimum film exposure are 1·04 (below 0·4 Hz) to 1·004 (7 – 12·5 Hz).

The values quoted above represent 'worst case' conditions. They have been adopted to ensure that very few of the viewing public perceive luminance fluctuations due to cyclic variations in the exposure of successive film frames. These values also assume that the fluctuation of display luminance is sinusoidal in character: it is possible that this assumption is not justified when the exposure cycle is short and occupies only a few film frames.

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   4a. Ibid. Fig. 42 (p. 70)
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   4c. Ibid. Fig. 43 (p. 71)
   4d. Ibid. Text, pp. 59 – 60.
   4e. Ibid. Fig. 33 (p. 55)

* A similar effect occurs when a sinusoidal waveform is sampled by a train of narrow pulses having double the sine-wave frequency. All the samples will be zero if they occur at the sine-wave crossing points, but alternately positive and negative if they occur elsewhere. The sample magnitudes will be greatest when the pulses occur at the peaks of the waveform.

* Remembering that a lower value of luminance fluctuation ratio represents an increase in the magnitude of the fluctuation itself.

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Appendix I

Scene Luminance and Retinal Illumination

Walsh[4d] defines the unit of retinal illumination as being the illumination produced on the retina by a surface having a luminance of one candela per square metre when the pupil area is one square millimetre. The unit is now usually named the 'troland', although the terms 'luxon' (used by Walsh[4]) and 'photon' (used by Dzn[9]) are also current. The conversion between scene luminance and retinal illumination values requires a knowledge of the state of adaptation of the eye (i.e. the pupillary area). In normal television viewing conditions this factor is not well defined since the intensity of the ambient illumination may differ considerably between different viewer's installations: furthermore, the mean picture luminance is variable, since it is dependant on picture content. In the comparisons given in Section 3.2 a pupillary diameter of 4 mm has been taken, corresponding[4e] to a field luminance of 7 cd m^{-2} (2 ft-L), this being the luminance of the area of background illumination provided as part of the EBU standard viewing conditions (see Section 2.2.2).

Appendix II

Co-Channel Interference Protection Ratios and Luminance Fluctuation Ratios for a Mean Grade of Unity

The conversion of co-channel interference protection ratio values into luminance fluctuation ratio values for a mean grade of unity involves a number of assumptions. These are itemised below, and in each case a factor is derived for converting the protection-ratio value into the luminance fluctuation ratio value (both these quantities are expressed in decibels). The sum of these factors is, in fact, zero (see item 6 below) and so the protection-ratio values are used directly in the comparison given in Section 3.2.

1. Units in which the two quantities are expressed

Protection-ratio values are given in terms of the ratio of the e.m.f.'s of the wanted and interfering signals present at the receiver input terminal, while luminance fluctuation ratio values are in terms of peak-to-peak fluctuation relative to the mean value (Equations (4) and (5)). As the interfering radio-frequency signal 'beats' with the wanted signal, it alternately cancels and reinforces the wanted signal: thus

the magnitude of the interference signal in the demodulated video signal is twice the value indicated by the ratio of the radio-frequency signals. Remembering that for both protection ratio and luminance fluctuation ratio an increase in the magnitude of the perturbing signal leads to a decrease of ratio value, the above consideration gives a conversion factor (C_1) of −6 dB.

2. Effects of radio-frequency interference and variation of film exposure

The effect of radio-frequency interference is to add a constant level of interference to all signal levels, while the effect of film exposure variations is to modulate the wanted signal with a constant ratio of perturbing signal. In the present case it has been noted that the test picture used for the co-channel interference tests[12a] contained a large 'light grey' area, having a transmission relative to white of about 75%. Assuming (see item 4 below) a gamma value of 2·5 in the display-tube input/output characteristic, this indicates a video signal of 90% of the peak value corresponding to this picture area. On the assumption that the luminance fluctuations were most noticeable in this large area during the co-channel interference tests, the ratio of signal perturbation to mean level is about 10% greater relative to this 90% signal level that to the peak signal. This leads to a conversion factor (C_2) of −1 dB.

3. Effect of modulation of the interfering signal during the co-channel interference tests

A modulated interfering signal was used during the co-channel interference tests, thus reducing by 4 dB the mean interfering signal level (the e.m.f. of a radio-frequency television signal is expressed in terms of the peak transmitted power, not the mean power). This leads to a conversion factor (C_3) of +4 dB (i.e. the interference level actually present was 4 dB less than the nominal value given by the protection ratio).

4. Effect of non-linearity of display tube

A television display tube has a power-law transfer characteristic (to a close approximation, especially for display luminance values well removed from picture black). Thus

$$L = kV^{\gamma}$$

where L is the display luminance

V is the video-signal drive potential

and k and γ are constants.

By the same process as used for the derivation of Equation (19) (Section 4.3) it can be seen that

$$\frac{\Delta L}{L} = \gamma \frac{\Delta V}{V}$$

where ΔL is a small luminance perturbation ($\Delta L \ll L$)

and ΔV is the corresponding drive-signal perturbation ($\Delta V \ll V$)

hence luminance perturbations are increased by a constant factor γ over the video-signal perturbations. In other co-channel interference work in progress at the same time as the results under discussion, a gamma value of 2·5 is quoted:[13] this leads to a conversion factor (C_4) of −8 dB.

5. Effect of different subjective criteria used in co-channel interference and present tests

Co-channel interference protection ratios were derived for a mean subjective grade (Table 1, Section 2.2.2) of 3·5, while the present work was based on a mean subjective grade of unity. Adopting the relationship of 4·4 dB per grade (see Section 3.1) leads to a conversion factor (C_5) of +11 dB.

6. Overall conversion factor

from items 1 – 5 above,

$$\begin{aligned} C_1 &= -6 \text{ dB} \\ C_2 &= -1 \text{ dB} \\ C_3 &= +4 \text{ dB} \\ C_4 &= -8 \text{ dB} \\ C_5 &= +11 \text{ dB} \end{aligned}$$

hence overall factor = 0 dB

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